International Journal of High-Rise Buildings
March 2016, Vol 5, No 1, 13-20

International Journal of
High-Rise Buildings
www.ctbuh-korea.org/ijhrb/index.php

Outrigger Systems for Structural Design of Complex-Shaped Tall Buildings

Kyoung Sun Moon†

Yale University School of Architecture, New Haven, CT 06511, USA

Abstract

Today's architecture can be best understood only through the recognition of pluralism, and, as is true of other building types, multiple design directions are prevalent for tall buildings. This contemporary design trend has produced many complex-shaped tall buildings, such as twisted, tilted and tapered form towers. Among many different structural systems developed for tall buildings, the outrigger system, with its inherent structural efficiency and flexibility in façade design, is widely used for contemporary tall buildings. This paper studies structural performance of outrigger systems employed for complex-shaped tall buildings. Twisted, tilted and tapered tall buildings are designed with outrigger structures, and their structural performance is investigated. For the twisted outrigger study, the buildings are twisted up to 3 degrees per floor. In the tilted outrigger study, the angles of tilting range from 0 to 13 degrees. The impact of eccentricity is investigated for gravity as well as lateral loads in tilted towers. In the study of tapered outrigger structures, the angles of tapering range from 0 to 3 degrees. Parametric structural models are generated using appropriate computer programs for these studies, and the models are exported to structural engineering software for design and analyses.

Keywords: Twisted tall buildings, Tilted tall buildings, Tapered tall buildings, Outrigger structures

1. Introduction

Today's pluralism in architecture has produced tall buildings of not only conventional prismatic forms but also more complex forms such as twisted, tilted and tapered forms. With its inherent structural efficiency and greater flexibility in façade design compared with perimeter tube type structures, the outrigger system is among the most widely used structural systems for today's tall buildings. The system was developed in the mid-twentieth century for tall buildings of prismatic forms. Today, with prevalent emergence of complex-shaped tall buildings, outrigger systems are often employed for the structural design of these complex-shaped tall buildings. Examples include the outrigger structures used for the twisted Chicago Spire project in Chicago and tilted Signature Towers project in Dubai designed by Santiago Calatrava and Zaha Hadid, respectively.

This paper investigates structural performance of outrigger systems employed for twisted, tilted and tapered tall buildings. Compared with shear wall type structures confined within the building core, outrigger structures carry wind-induced overturning moments much more efficiently with greater structural depth by connecting perimeter mega-columns to stiff building cores through outrigger trusses. The outrigger system's lateral load carrying mechanism is conceptually explained in Fig. 1. The overturning moment (Mo) caused by wind loads (W) is reduced due to the counteracting moment (Mc) provided by the mega-columns connected to the building core through the outrigger trusses. The counteracting moment can be expressed as

$$M_c = 2b^2 AE\chi$$

A is sectional area of mega-columns; E is modulus of elasticity of steel, assuming steel is used; χ is curvature. Since the modulus of elasticity of steel is almost constant regardless of its strength, the outrigger's bending rigidity is a function of the square of the building width and sectional area of the mega-columns.

In order to illustrate the concepts underlying the structural behavior of twisted, tilted and tapered tall buildings of outrigger systems, parametric structural models are generated using appropriate computer programs such as Rhino/Grasshopper to investigate the impact of varying rates of twist, angles of tilt and angles of taper. The models are exported to structural engineering software, SAP 2000, for design, analyses and comparative studies.

2. Twisted Outrigger Structures

Employing twisted forms for tall buildings is a recent architectural phenomenon, as are the cases with the Shanghai Tower in Shanghai designed by Gensler, Infinity Tower

†Corresponding author: Kyoung Sun Moon
Tel: +1-203-436-8983; Fax: +1-203-432-7175
E-mail: kyoung.moon@yale.edu

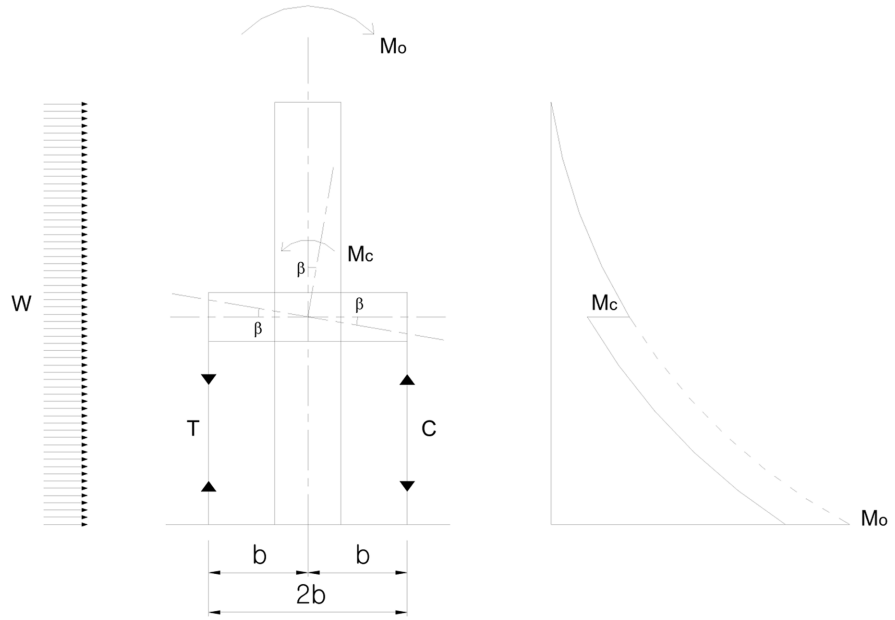


Figure 1. Lateral load carrying mechanism of outrigger structural system.

in Dubai by SOM, and Chicago Spire project in Chicago by Calatrava. While structures of rectangular box forms are very common and have been one of the most extensively researched subjects, structures of twisted forms are relatively rare and have not been investigated much.

Design studies on twisted outrigger structures are carried out with 60-story buildings. A non-twisted straight outrigger structure is designed first. The building's typical plan dimensions are 36×36 meters with an 18×18-meter braced core at the center and typical story heights of 3.9 meters. The outrigger trusses are located at the top and mid-height of the tower. There are 8 perimeter mega-columns connected to the steel braced core through the outrigger trusses as can be seen in Fig. 2. The SEI/ASCE Minimum Design Loads for Buildings and Other Structures is used to establish the wind load. The structures are assumed to be in Chicago. Based on the code, the basic wind speed is 40.2 meters per second (90 miles per hour).

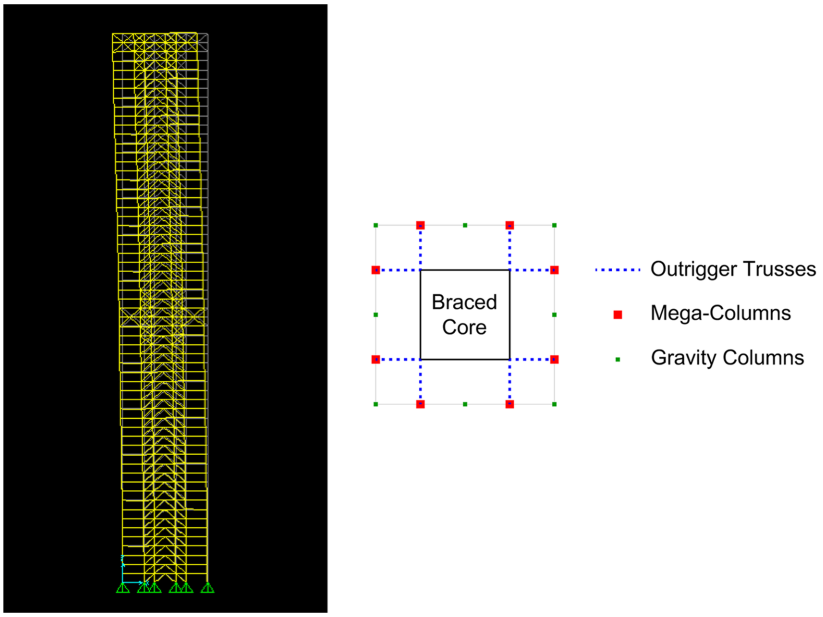


Figure 2. Laterally deformed section and simplified plan of the 60-story outrigger structure.

In terms of the geometric configuration of twisted outrigger structures, two cases are studied comparatively. The first case uses spirally slanted perimeter mega-columns in response to the twisted building form. In this case, the location of the mega-columns gradually changes along the building height. The second case uses vertical mega-columns, set back from the building perimeter, and cantilevered floor slabs from the column lines. Even if the original structural concept of the outrigger system is maintained in this case, the structural depth against lateral loads is reduced by setting back the mega-columns from the extreme building perimeter.

Structural design of tall buildings is generally governed by lateral stiffness rather than strength (Connor, 2003; Ali & Moon, 2007). Member sizes for the non-twisted straight outrigger structure are generated first to satisfy the maximum lateral displacement requirement of a five hundredth of the building height at the top. In order to comparatively estimate the structural effectiveness of outrigger structures employed for twisted towers, the member sizes used for the straight outrigger tower are also used for twisted ones. Thus, each structure was designed with very similar amount of structural materials.

The optimal lateral stiffness distribution between the braced core and the perimeter mega-columns was investigated through many design studies of outrigger tall buildings with the depth of the braced core of 18 meters and the distance between the opposite side mega-columns of 36 meters. Based on the study results, it was determined to distribute 40% of the lateral bending stiffness to the braced core structure, and 60%, to the perimeter mega-columns (Moon, 2014). Lateral shear stiffness is provided entirely by the braced cores.

2.1. Twisted outrigger structures with spirally slanted perimeter mega-columns

The 60-story outrigger structure is twisted with two different rates. The first case twists the tower by 1.5 degrees per floor, which results in a total turn of 90 degrees. The mega-columns on the building perimeter wrap around the building spirally. Therefore, the position of the mega-columns on the flange planes (i.e., planes perpendicular to wind) at the base changes to those on the web planes (i.e., planes parallel to wind) at the top. And the position of the mega-columns on the web planes at the base changes to those on the flange planes at the top. The second case twists the tower by 3 degrees per floor, which results in a total turn of 180 degrees. In this case, the position of the mega-columns on the flange planes at the base changes to those on the web planes at mid-height, and finally to those on the opposite flange planes at the top as can be seen in Fig. 3.

Fig. 4 summarizes deformed shapes of the outrigger structures shown in Figs. 2 and 3, as well as the case with setback vertical mega-columns and inset outriggers (Fig. 7) which will be discussed in the following section. As can be seen from the figure, the lateral stiffness of the outrigger structures is reduced and the stiffness reduction rate is accelerated as the rate of twist is increased. In both the straight outrigger and the twisted outrigger with a rate of twist of 1.5 degrees per floor, curvature reversals clearly occur around the outrigger truss levels. However, in the case with a rate of twist of 3 degrees per floor, it is difficult to see the curvature reversals. The case with the rate of twist of 3 degrees per floor behaves more like a cantilever beam without outriggers in general, compared with typical outrigger structures in which curvature rever-

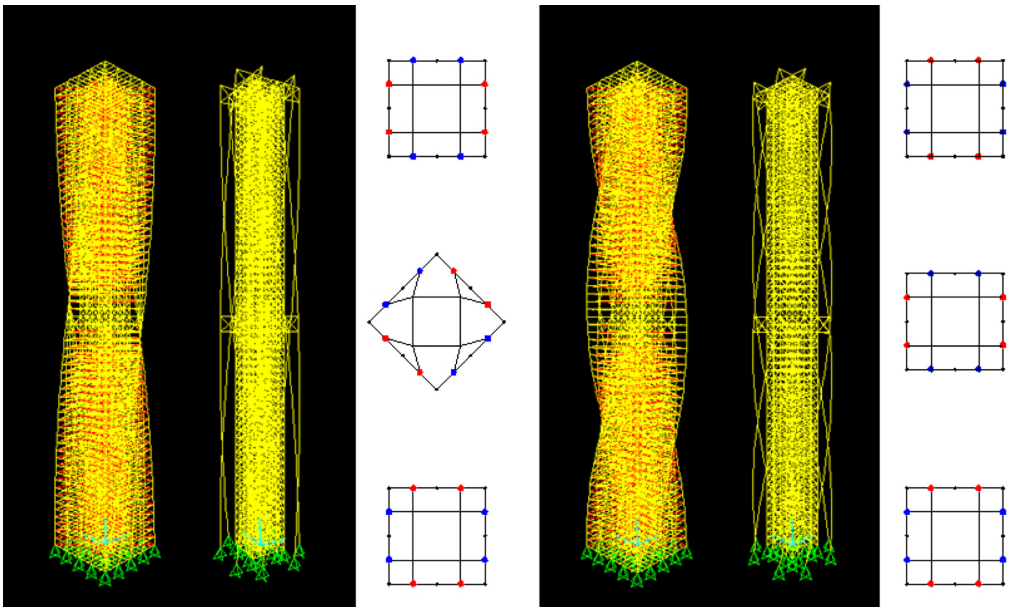


Figure 3. 60-story outrigger structures with 1.5- and 3-degree turn per floor.

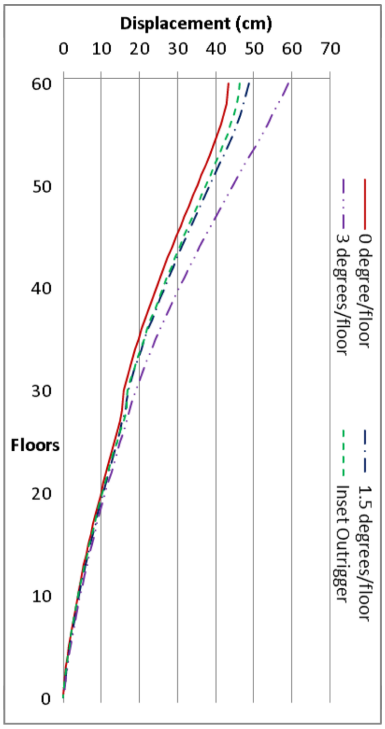


Figure 4. Deformed shapes of the twisted 60-story outrigger structures subjected to wind loads.

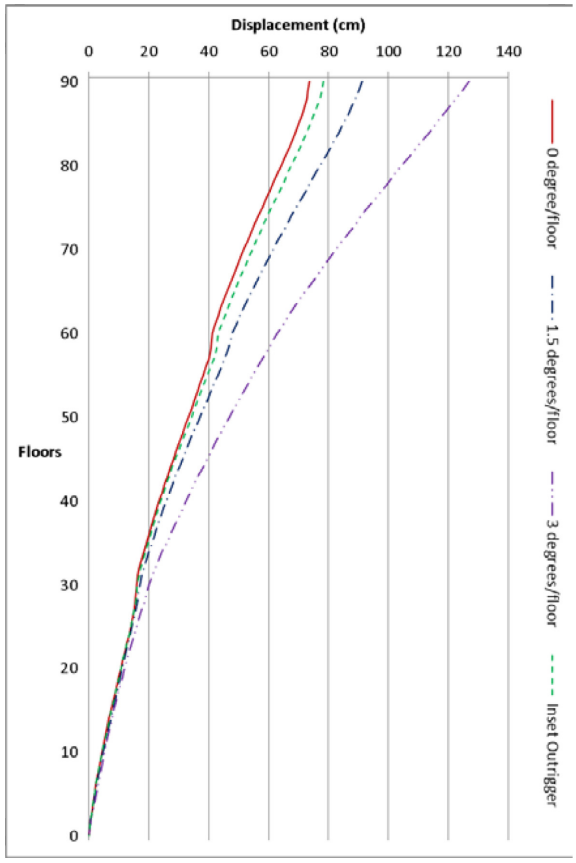


Figure 5. Deformed shapes of the twisted 90-story outrigger structures subjected to wind loads.

sals occur.

Similar studies are conducted with 90-story outrigger structures with outrigger trusses located at the top as well as one-third and two-third heights of the building. The building's height-to-width aspect ratio is 9.8. A non-twisted straight 90-story outrigger building is studied first, and then the tower is twisted with two different rates. The first case twists the tower by 1.5 degrees per floor, which results in a total turn of 135 degrees. The second case twists the tower by 3 degrees per floor, which results in a total turn of 270 degrees. Study results are similar to those obtained from the 60-story twisted outrigger towers. Fig. 5 shows deformed shapes of the straight and two twisted 90-story outrigger structures, as well as the case with setback vertical mega-columns and inset outriggers which will be discussed in the following section.

Fig. 6 summarizes the maximum lateral displacements of the 60- and 90-story outrigger structures studied in this section. The lateral stiffness of the outrigger structures is reduced and the stiffness reduction rate is accelerated as the rate of twist is increased. As the height of the structure is increased, the rate of the stiffness reduction caused by twisting the tower is also accelerated.

2.2. Outrigger structures with setback vertical mega-columns

The next case studied is the lateral performance of the 60-story twisted outrigger structure with setback vertical mega-columns. Compared with the straight tower case, the vertical mega-columns are located about 1.5 meter set back from the building perimeter. Consequently, the structural depth of the building against wind loads is reduced by about 3 meters, and the maximum lateral displacement is increased by about 3 cm compared with the original case of the straight tower with the perimeter mega-columns. However, this configuration still produces higher lateral stiffness than the previous cases with spirally slanted perimeter mega-columns. A similar study was conducted with a 90-story twisted outrigger structure with setback vertical mega-columns. By setting back the vertical mega-columns, the maximum lateral displacement of the twisted 90-story outrigger structure is increased by about 5 cm. Deformed shapes of the 60- and 90-story twisted outrigger structures with setback vertical mega-columns are shown in Figs. 4 and 5, respectively.

3. Tilted Outrigger Structures

Buildings have traditionally been constructed vertically, orthogonal to the ground. When a building is found to be tilted, it is typically an indication of some serious problems occurred to the building. Today, however, tilted buil-

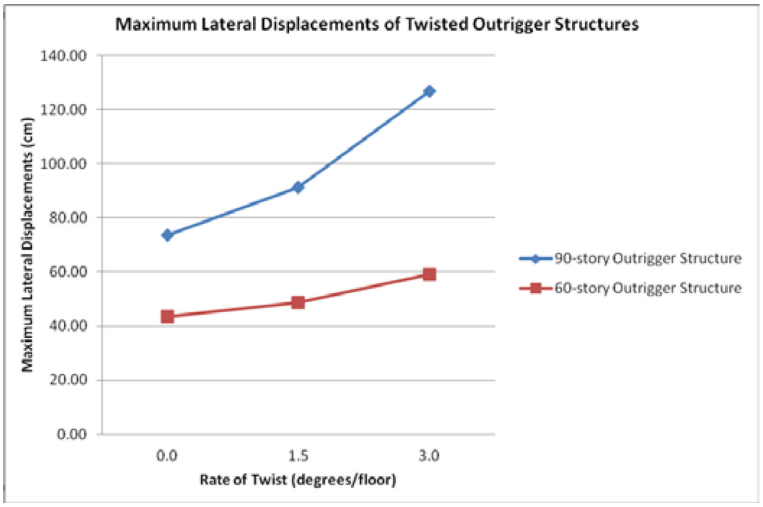


Figure 6. Maximum lateral displacements of twisted outrigger structures.

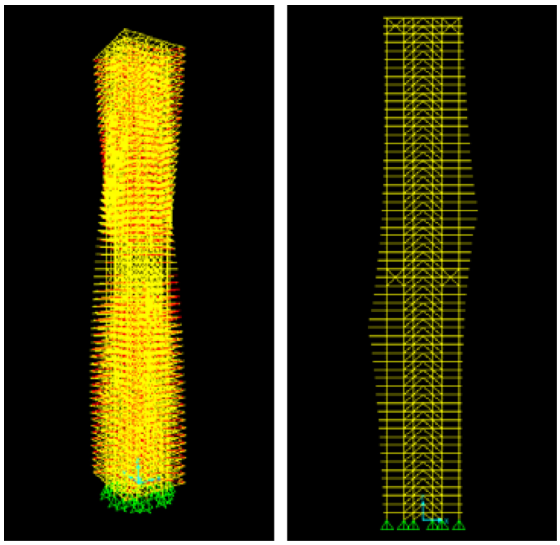


Figure 7. 60-story twisted outrigger structure with vertical setback mega-columns: 3D image (left) and 2D section (right) at the plane of outrigger trusses.

dings are intentionally designed and built to produce more dramatic architecture, as are the cases with the Gate of Europe Towers in Madrid designed by Philip Johnson/John Burgee, Veer Towers in Las Vegas by Helmut Jahn, and the design of the Signature Towers in Dubai by Zaha Hadid.

The 60-story buildings are now tilted and designed with outrigger systems to study the structural performance of the system employed for tilted tall buildings. Fig. 8 shows the straight outrigger structure and its four different tilted versions. Design conditions, including the applied wind loads, are the same as before. The second case is a tilted case with no floor offset. While the 18×18-meter braced core is kept vertical within the tilted building mass, the building is tilted to its maximum angle of 4 degrees. Therefore, on the left side of the building as seen in Fig. 8, the distance between the exterior façade and the core perimeter wall reduces from 18 meters on the ground to 0 meter at the top. On the right side, this distance increases from 0 meter on the ground to 18 meters at the top. The tilted form of this case is similar to that of the Gate of Europe Towers in Madrid or the Veer Towers in Las Vegas.

The third, fourth and fifth cases are tilted outrigger towers with floor offsets of 12, 16 and 20 stories at both the top and bottom, resulting in tilted angles of 7, 9 and 13 degrees, respectively. In these cases, the 18×18-meter gravity cores are still kept vertical within the tilted building mass. Tilted forms of these cases are similar to those of the Signature Towers project for Dubai designed by Zaha Hadid.

The outrigger trusses in tilted towers are now placed approximately at a third and two third heights of the building. For the optimum performance, the outrigger in a one outrigger structure should be at about half height; the outriggers in a two outrigger structure should be at about one-third and two-thirds heights; the outriggers in a three outrigger structure should be at about one-quarter, one-half, and three-quarters heights, and so on (Taranath, 1998; Smith and Coull, 1991). The locations of these outrigger trusses are adjusted for enhanced constructability depending on the offset locations of the tilted towers as can be seen in Fig. 8. In the previous study on the twisted outrigger structures, the locations of the outriggers were also adjusted to enhance constructability.

Structural design is performed for the straight outrigger structure first to satisfy the maximum lateral displacement requirement of a five hundredth of the building height. The member sizes for the braced core and mega-columns of the straight outrigger structure are also used for the tilted outrigger structures, for preliminary designs. The outrigger

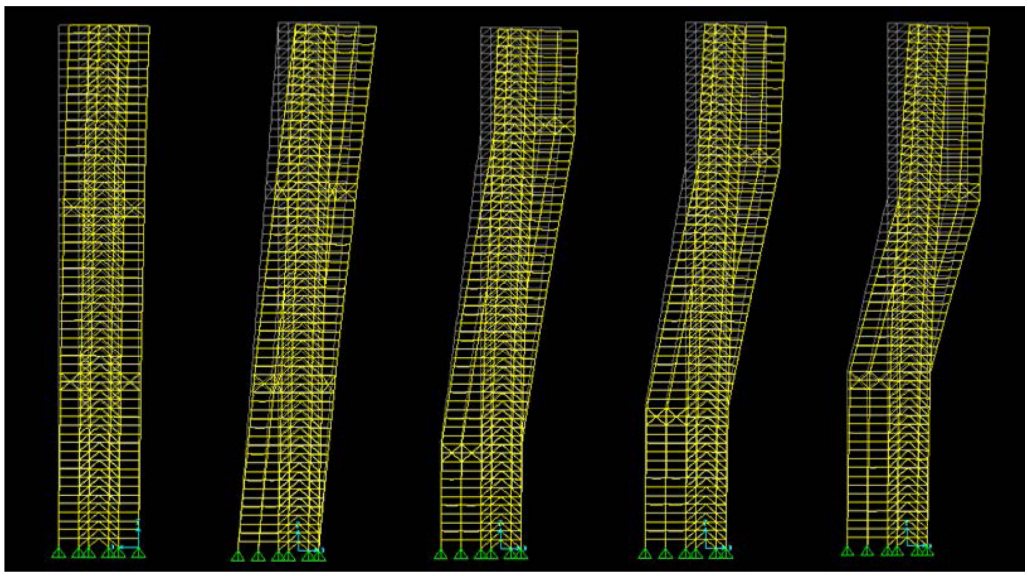


Figure 8. 60-story tilted outrigger structures with tilted angles of 0, 4, 7, 9 and 13 degrees.

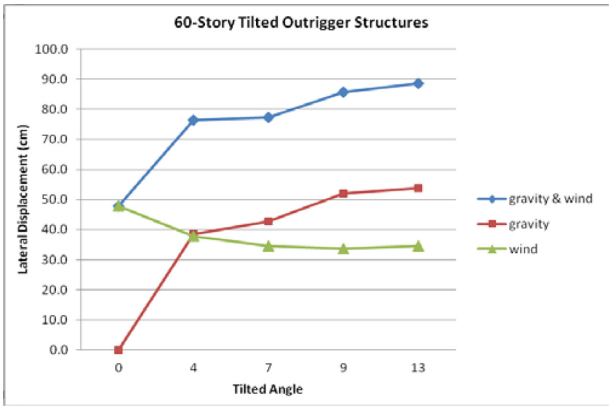


Figure 9. Lateral displacements of 60-story tilted outrigger structures with tilted angles of 0, 4, 7, 9 and 13 degrees.

truss member sizes are adjusted according to the length of the trusses. Overall, similar amount of structural materials are used for the five cases studied.

Fig. 9 and Table 1 summarize the maximum lateral displacements of the tilted outrigger structures in the direction parallel to the direction of tilting, when the wind load is also applied in the same direction. It was found that lateral stiffness of the tilted outrigger structures against wind loads is greater than that of the straight outrigger structure. The tilted outrigger structures configured as shown in Fig. 8 carry lateral loads more effectively because tilting the tower results in triangulation of the major structural components - the braced core, mega-columns and outrigger trusses. As the angle of tilting is increased from 0 to 13 degrees, the geometry of the triangles, formed by the major structural components, becomes even more effective to resist the wind load, and, consequently, the wind-induced maximum lateral displacement of the outrigger structure is decreased. However, the gravity-induced lateral deformation is increased as the angle of tilting is increased. This gravity-induced deformation could be managed substantially during construction if planned carefully.

4. Tapered Outrigger Structures

Compared with prismatic forms, tapered forms provide many advantageous aspects for structural systems of tall buildings. As has been discussed, for very tall buildings, it is common that lateral stiffness requirements against wind loads govern the structural design. The magnitudes

Table 1. Maximum lateral displacements of the tilted outrigger structures shown in Fig. 8

	Tilted Angle (degrees)	Gravity-Induced Max. Lateral Displacement (cm)	Wind-Induced Max. Lateral Displacement (cm)	Combined Max. Lateral Displacement (cm)
Straight	0	0.0	47.8	47.8
0 Fl Offset	4	38.6	37.9	76.5
12 Fl Offset	9	42.7	34.6	77.3
16 Fl Offset	7	52.0	33.6	85.6
20 Fl Offset	13	53.9	34.6	88.5

of lateral shear forces and overturning moments due to lateral loads become larger toward the base of the building. Consequently, greater lateral stiffness is required at lower levels. Tapered forms provide greater lateral stiffness toward the base because tapered forms naturally produce greater structural depth toward the base.

Tapered forms also help reduce wind loads applied to tall buildings. When a building is tapered, the exterior surface area where the wind load is applied is reduced at higher levels, and increased at lower levels. Since wind pressure is greater at higher levels and lesser at lower levels, the shear and overturning moments at each level is decreased as the angle of taper is increased.

The 60-story outrigger structure is now tapered with three different angles of 1, 2 and 3 degrees as shown in Fig. 10. Since the building width at the mid-height is maintained the same as the original straight tower, each building's gross area is identical regardless of the different angles of taper. The size of the interior braced core at the center - 18×18 meters - is kept identical along the height of the building, while the overall building form is tapered. Therefore, the distances between the opposite side perimeter mega-columns, which act as counteracting moment arms, become greater towards the base, where greater overturning moments are exerted, and narrower towards the top. This configuration helps increasing lateral stiffness of the system. The length of the lower outrigger trusses, however, becomes longer as the angle of taper is increased. In outrigger structures with multiple outriggers, the lowest outrigger induces the maximum resisting moment and the outriggers above carry successively less (Wu and Li, 2003; Taranath, 1998). The increased length of the lower outrigger trusses reduces the stiffness of the trusses and consequently adversely contributes to increasing the lateral stiffness of the system. However, the increased stiffness based on tapering the structure still governs the system's overall performance.

The maximum lateral displacements of the 60-story tapered outrigger structures shown in Fig. 10 as well as similarly configured and designed 80- and 100-story tapered outrigger structures are summarized in Fig. 11. Lateral displacements of outrigger structures are reduced as the angle of taper is increased and the impact of taper becomes greater as the building becomes taller.

5. Conclusions

Early design of tall buildings culminated with the emergence of the International Style, which produced many Miesian towers all over the world for decades. Today, however, as is true of other building types, multiple design directions are prevalent for tall buildings. This contemporary design trend has produced various building forms, such as twisted, tilted and tapered forms.

This paper studied lateral stiffness of outrigger structures employed for twisted, tilted and tapered tall build-

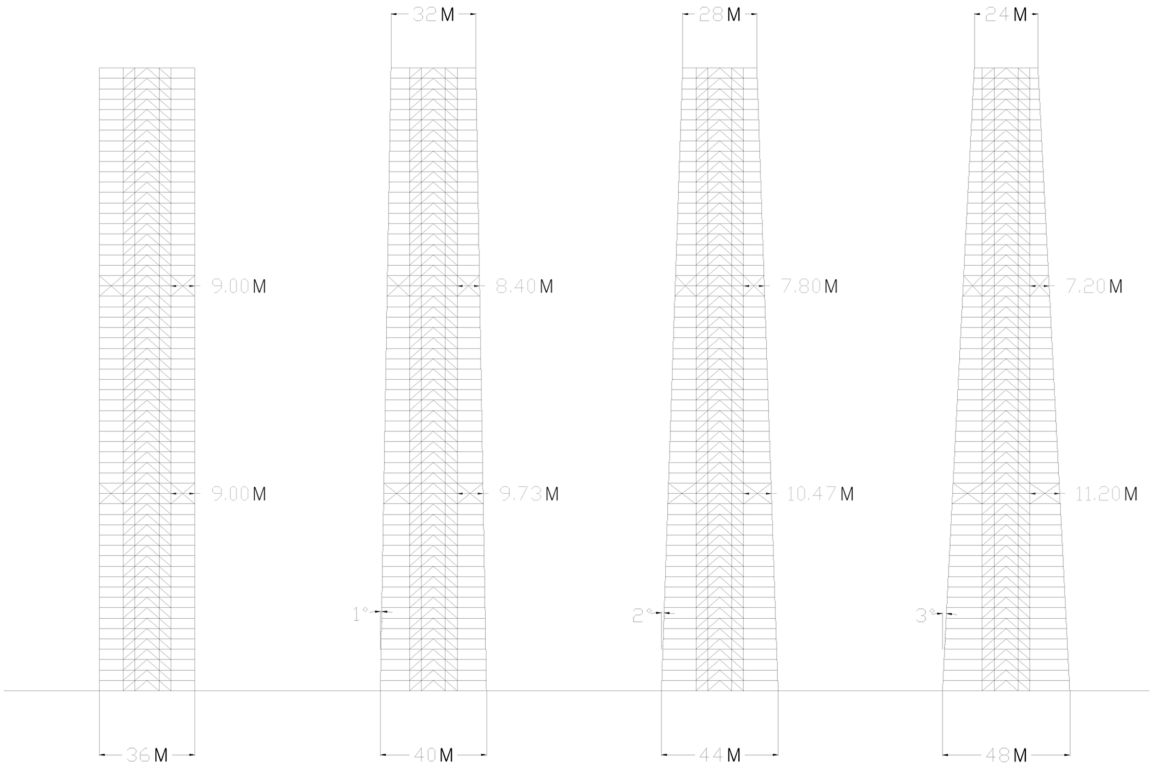


Figure 10. Tapered 60-story outrigger structures.

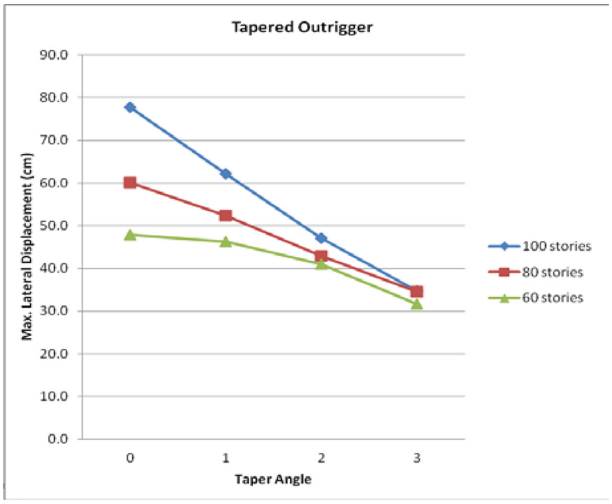


Figure 11. Maximum lateral displacements of the 60-story tapered outrigger structures shown in Fig. 10.

ings. When the outrigger system with perimeter mega-columns is employed for twisted tall buildings, its lateral stiffness is reduced as the rate of twist is increased. However, when the system is used for tapered tall buildings, its lateral stiffness is increased as the rate of taper is increased. In tilted towers, the outrigger system's lateral stiffness is also increased due to the triangulation of the primary structural components of the system - braced core, outrigger trusses and perimeter mega-columns, while gravity-induced initial lateral deformation becomes substantial.

The unique compositional characteristics of outrigger structures provide great structural efficiency and aesthetic potential for complex-shaped tall buildings. With abundant emergence of complex-shaped tall buildings, including twisted, tilted and tapered towers, more studies on their structural systems and systems integration through multi-disciplinary collaboration are very much required to construct built environments of higher performance.

References

Ali, M. M. and Moon, K. (2007). Structural Developments in Tall Buildings: Currents Trends and Future Prospects. *Architectural Science Review*, 50(3), 205-223.

Connor, J. J. (2003). *Introduction to Structural Motion Control*. New York: Prentice Hall.

Kowalczyk, R., Sinn, R., and Kilmister, M. B. (1995). *Structural Systems for Tall Buildings.* Council on Tall Buildings and Urban Habitat Monograph. New York: McGraw-Hill.

Moon, K. (2014). Studies on various structural system design options for twisted tall buildings and their performances. *The Structural Design of Tall and Special Buildings*, 23(5), 319-333.

Moon, K. (2014). Comparative evaluation of structural systems for tilted tall buildings. *International Journal of High-Rise Buildings*, 3(2), 89-98.

Simiu, E. and Scanlan, R. H. (1996). *Wind Effects on Structures: Fundamentals and Applications to Design*. 3rd Edition. New York: Wiley.

Smith, B. and Coull, A. (1991). Tall Building Structures: Analysis and Design. New York: Wiley.

Taranath, B. (1998). *Steel, Concrete, & Composite Design of Tall Buildings*. New York: McGraw-Hill.

Wu, J. R. and Li, Q. S. (2003). Structural performance of multi-outrigger braced tall buildings. *The Structural Design of Tall and Special Buildings*, 12, 155-176.